Creating a multifunctional composite stator slot material system to enable high power density electric machines for electrified aircraft applications

Andrew A. Woodworth and Ralph Jansen
NASA Glenn Research Center

Kirsten Duffy
University of Toledo

Paria Naghipour and Euy-Sik Shin
Ohio Aerospace Institute

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Electric Machine Motivation: STARC-ABL

Conventional tube and wing design along with minimal battery dependence makes this a near term possibility (2030ish)

### Electrical Machines
- Two 1.4 MW generators mounted near turbines
- One 2.6 MW motor driving tail cone thruster

### Geared Turbofan
- HP Spool = ? rpm
- LP Spool = 6800 rpm (generator connects here)

### Tailcone Thruster
- Fan = 2514 rpm
- Diameter = 80.2"
- Hub/Tip Ratio = 0.3
- Hub Diameter = 24.1"

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**Cooling Loop**

<table>
<thead>
<tr>
<th></th>
<th>°C</th>
<th>°F</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant</td>
<td>60</td>
<td>140</td>
<td>333</td>
</tr>
<tr>
<td>Oil</td>
<td>135</td>
<td>275</td>
<td>408</td>
</tr>
</tbody>
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UTRC Concept for HGEP Thermal Management

High Power Density Electric Machine
Electric Machine Motivation: NASA Efforts

- Internal NASA motor development
  - Target >98% Efficiency Stretch Goal 99%
  - 16 kW/kg
  - 1.46 MW
- External NASA funded motor development
  - >13 kW/kg
  - >1 MW
  - >96% Efficient
  - Teams at UIUC & OSU
- All teams have chosen Litz wire or form wound conductors to meet their goals
- High power densities = higher temperatures = more loss (10 °C increase in temperature is a 3.9% increase in resistive loss)

NASA NRA: High Power Density Motor Under Development by Professor Haran’s Group, University of Illinois Urbana-Champaign. Contracting Officer Representative Andrew Provenza, NASA Glenn Research Center
Litz Wire

- Litz wire reduces losses due to induced eddy currents
- Parallel conduction of current in the motor-strands at roughly the same potential
  - Standard magnet wire electrical insulation on each strand is a significant over design
- Litz wire offers a unique design space for new material solutions
Inside a Stator Slot

Slot
- soft magnetic material

Wire insulation
- electric isolation, polyimde ~0.1 W/m-K

HV Insulation
- electrical isolation, polyamide or mica (1-2W/m-K)

Potting material
- mechanical stabilization/thermal management*
- epoxy ~2W/m-K (with some exceptions)

Potted AWG 38 (101 micrometer diameter) with a heavy build polyimde insulation
Thermal Effects: Potting Material vs. Wire Insulation

From the law of mixtures

\[ K_{\text{transverse}} = \frac{1}{\frac{\eta_{\text{Cu}}}{K_{\text{Cu}}} + \frac{\eta_{\text{ins}}}{K_{\text{ins}}} + \frac{\eta_{\text{epoxy}}}{K_{\text{epoxy}}}} \]

\[ K_{\text{axial}} = K_{\text{Cu}} \eta_{\text{Cu}} + K_{\text{ins}} \eta_{\text{ins}} + K_{\text{epoxy}} \eta_{\text{epoxy}} \]

- Increasing the thermal conductivity of the potting material (epoxy) has a significant effect on thermal conductivity
- Wire insulation is a significant thermal choke
- Does ins the traditional wire insulation necessary with Litz wire—could it be replaced with the potting material
Finite Element Analysis (FEA) of the High Voltage Insulation

High voltage insulation breakdown (> 2x operating voltage of the motor) is necessary between phases in a stator slot and between the conductor and back iron.

FEA of a theoretical motor slot. High voltage insulation wraps each Litz wire. High voltage insulation thermal conductivity (a) 0.12 W/m-K and (b) 0.24 W/m-K.
Rudimentary Unit Cells (RUC)

RUCs allow for rapid reproduction of common (repeated) structures in a composite material.
High Fidelity Generalized Method of Cells (HFGMC)

Provides a 10x increase in computational speed while minting most of the accuracy of FEA

Makes computations of large number of the repeated structures possible
Preliminary Micro Thermal Modeling Results

Hexagonal
Conductor ~ 55-60%
Insulator ~20%-30%
Potting material~15-20%

Square
<K║ = 380 W/m-K
K┴22 = 0.79750 W/m-K
K┴33 = 0.79529 W/m-K

Random I and II
Conductor: 45-50%
Insulator: 20%-30%
Potting material: 25-30%

Random-I
<K║ = 240 W/m-K
K┴22 = 0.442 W/m-K
K┴33 = 0.421 W/m-K

Random-II
<K║ = 255 W/m-K
K┴22 = 0.528 W/m-K
K┴33 = 0.524 W/m-K
Summary & Conclusions

- Conceptualizing the insulation materials systems as composite is the key gaining to multi-functionality
  - Electrical
  - Thermal
  - Mechanical
- Composite approach provides modest, achievable goals can be set. thermal conductivities for
  - potting materials > 1 W/m-K, and
  - High Voltage Insulation ~ 0.5 W-m/K
  - possibly replacing or eliminating the insulation material on the Litz wire. These
  - goals are backed up by finite element modeling.
- Higher fidelity micro thermal modeling along with testing and model validation will bring more clarity to how the physical system behaves and will also refine the material development goals.
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